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A LOW-LEVEL JET IN THE TROPICS

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ABSTRACT

A temporary mesoscale network of pilot balloon stations on a tropical island (Barbados, West Indies) revealed the existence of a low-level jet at 700 m above mean sea level, with a maximum wind near 40 m/s and a duration of at least 2 hr. The phenomenon appears to be associated with the Venturi effect produced in the low levels by a traveling gravity wave at the inversion. It is suggested that jets of this kind probably exist over other tropical islands.

1. INTRODUCTION

During July 1969, a mesoscale pilot balloon network, shown in figure 1A, was temporarily established on the island of Barbados as a part of the Florida State University Field Experiment. The pilot balloon array was operated within a network of observing stations described by Garstang and LaSeur (1968). A total of 250 soundings were made over a period of 5 days, with a release rate of 1/hr during daylight hours. The objective of the pilot balloon program was to obtain detailed wind measurements in the lowest 2000 m of the tropical troposphere for the purpose of calculating mass divergence. On July 16, 1969, a very pronounced low-level easterly jet was detected over the central portion of the island. The phenomenon of a low-level jet is not uncommon in middle latitudes (Hoecker 1963, Izumi and Barad 1963, Findlater 1969, and Sweeney 1969), except that, in most instances, it is frictionally induced in the Ekman layer and has a typical duration of half a pendulum day or longer (Hsueh 1970). The relatively confined jet observed over Barbados appears to be associated with the Venturi effect produced by a traveling gravity wave at the base of the inversion that was clearly present in the lower troposphere.

The theoretical possibility of waves upstream from a perturbing obstacle in a flow of stably stratified viscous fluid has long been known (Rayleigh 1883). The apparently wavelike structure of the observed winds over the island may well have been produced upstream and carried across Barbados by the prevailing winds. The presentation of available information and some discussion as to the formation of the jet due to such wavelike disturbances form the basis for this paper.

2. OBSERVATION AND ANALYSIS

Barbados, the easternmost island of the Lesser Antilles, is located near 13°N, 60°W. The steadiness of the surface wind field is typical of locations embedded in the deep easterlies of the western reaches of tropical oceans. The island is 430 km^2 (30 km in the north-south direction and 20 km in the east-west direction). Figure 1A shows the outline of Barbados with the 120- and 240-m contours above mean sea level (MSL) illustrating the moderate relief of an uplifted coral island. The sites of the pilot balloon stations, as located on July 16, 1969, are also shown.

Balloons were tracked by the single-theodolite method. The accuracy of this method was checked by the use of a tracking radar as outlined below. Radios at each site were used to synchronize balloon releases. A 30-g balloon was released every hour during daylight hours with a rate of rise of 150 m/min. Angular readings were taken every 30 s for a period of not more than 30 min. As an explicit check on the actual rate of rise, some balloons were equipped with reflectors and tracked by an M–33 radar system located at site 2 (fig. 1A). It was found that the deviations from the assumed constant rate of rise were small and the rate of ascent was always slightly less than 150 m/min (i.e., characteristically the balloon would be at 1900 m when assumed to be at 2000 m). Care was taken to weigh off every balloon in exactly the same manner. Azimuth angles were read to the nearest 0.1°. These data were transferred to punch cards for computer evaluation of the winds. The u and v components of the winds obtained are presented in time cross-sections for July 16, 1969, in figure 2. Figures 2A–2E show time sections of the u component of the horizontal wind velocity at each of these five stations. Maximum speeds of 35.8 m/s recorded at a height of 450 m above ground level (700 m above MSL) are reported at 1134 LST (1534 GMT) at the Cottage (station 2). Soundings from all stations show a wind maximum in the region of 200–1000 m. The easternmost station, East Point (3), shows a rather weak maximum. Corresponding figures for the v component are presented in figures 2F–2J. A significant northerly component exists, with a defined region of maximum winds between 200–1000 m at all stations. Once again, the maximum value of 16.4 m/s is recorded at Cottage at 1134 LST (1534 GMT). The dotted areas in figures 2F–2J show that there is a continuous layer of southeasterly winds overlying the strong northeasterly trades at four of the stations. Figures 1B–1D show the spatial distribution of the u component at the level of maximum u at each station over a 3-hr period. The observations are supplemented when possible by cloud velocities computed from time-lapse cameras oriented to the north of the network of pilot balloon stations. If the degree of subjectivity required to represent the scalar speed is granted, then it is clear that the velocity maximum near Cottage at 1130 LST (1530 GMT) migrates to the southwest and diminishes in intensity.

These data represent sufficient temporal and spatial continuity to conclude that significant gradients existed in the low-level wind field over the island on this particular day. It is considered that such gradients and velocities justify labeling the region of maximun winds as a "jet." These conditions differ substantially from the more usual low-level trade wind regime (Charnock et al. 1956, Riehl 1954) where, typically, a maximum wind speed of 6–8 m/s occurs at a level of about 900–1000 m.

Rawinsonde ascents were made at Seawell Airport (Barbados Meteorological Service) twice per day and at Paragon House (Barbados Oceanographic and Meteorological Experiment) at varying rates up to one per 3 hr. Two soundings from Seawell immediately prior to the occurrence of the observed high winds and one sounding after its occurrence are reproduced in figure 3. Subsidence inversions (labeled A at 0000 GMT on July 16, AA at 1200 GMT on July 16, and AAA at 0000 GMT on July 17) are present in the temperature curves. The heights of these inversions decreased over the 12-hr period before the jet and the moisture content below 700 mb decreased substantially. The inversion base was the same after the jet; but the top lowered, indicating continued intensification of the inversion. Assuming that the 0800 LST (1200 GMT) Seawell sounding is, in general, representative of the large-scale conditions over Barbados and that these conditions persisted during the morning of July 16, 1969, the maximum velocity core near site 2 would then lie near the base of the lowest subsidence inversion (AA).

Further evidence for the existence of the high velocity core close to the base of the inversion is shown by the low-level clouds. In figure 4A, a panoramic view of the clouds is presented for 1100 LST (1500 GMT), close to the time when the jet was observed. The photographs were taken from station 2. The fragmented appearance of the clouds is very evident. For comparison, figure 4B shows the cloud cover for a typical day taken from the same site and at the same hour (3 days earlier). On this day, the corresponding maximum winds were about 7 m/s. No low-level subsidence inversion was present.

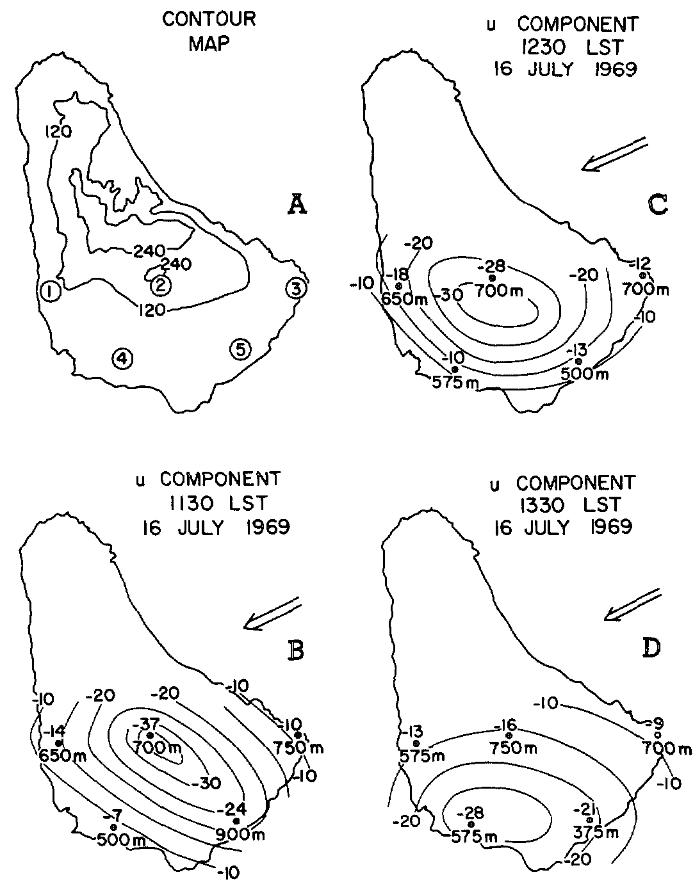

FIGURE 1.—(A) contours (m) and locations of stations 1–5; (B) scalar analysis of the u component of the wind (m/s) at the level of maximum wind at 1130 LST on July 16, 1969. The arrow indicates the prevailing wind direction in the lowest 750 m; (C) and (D) are the same as (B) except for the time and date.

3. DISCUSSION

During a day with marked subsidence, convective activity is generally suppressed due to large-scale sinking and accompanying adiabatic warming and drying. Typically, inversions form under these conditions. With humid air below and dry air above the inversion base, longwave radiation cooling effects may be enhanced to such an extent as to produce superadiabatic conditions below the inversion layer. In this particular case, a distinct temperature inversion developed with a superadiabatic lapse rate existing between the ground and the inversion at 1200 GMT on July 16 (fig. 3). It is suggested that these inversion conditions point to the likely initiation of upstream gravity waves due to the blocking effect of the island downstream in the easterly current.

Figures 1B–1D together with figures 2A–2J suggest that there is a wavelike undulation with continuity in space and time. With evidence that the undulation has

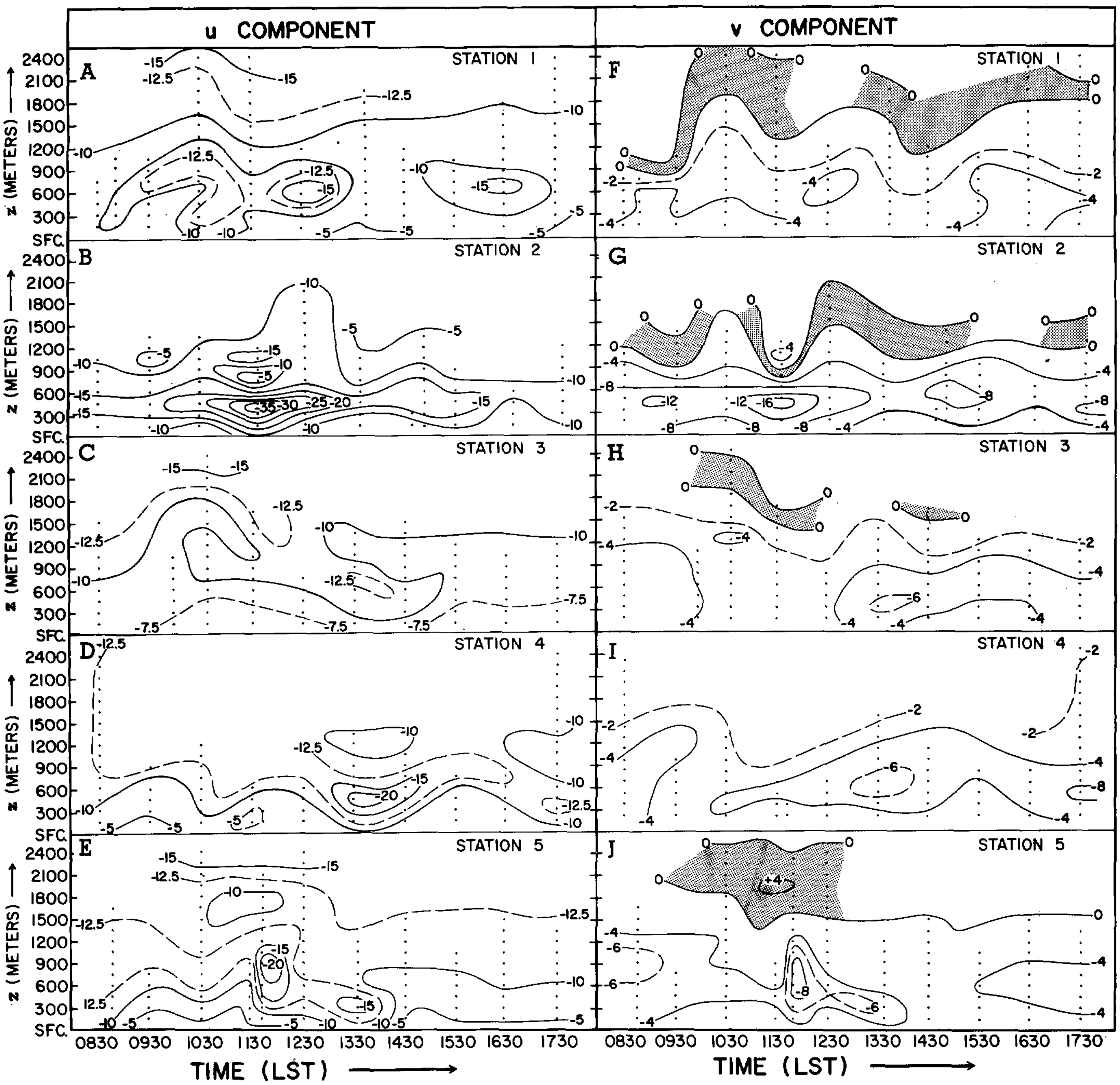

FIGURE 2.—(A) time section of the u component of the wind (m/s) for station 1. Easterly winds are shown as negative values. Heights are in meters above the station surface. The numerical values upon which the analysis is based are not shown, but the vertical and temporal distributions of the data are represented by dotted lines; (B–E) are the same as (A) except for station numbers; (F) is the time section of the v component of the wind (m/s) for station 1. North winds are shown as negative values. Regions of southerly winds are shaded. Heights are in meters above the station surface. As in (A), the locations of the data are shown by dotted lines; (G–J) are the same as (F) except for station numbers.

spatial continuity, the time sections presented in figure 2 might suggest that it is most pronounced in the wind field above the inversion (AA). It is further noted that the wind veers considerably with height throughout the lowest 2000 m. As the gradient Richardson number is quite large and positive ($\sim$0.5) except during the occurrence of the jet, when the Richardson number is about 0.1 due to the large shear through the inversion, the mixing between winds at different heights can be expected to be slight. As a result, it may be argued that the undulation of the narrow belt of southeasterly winds ($+v$ component) represents with some accuracy a gravity wave caused by the island which forces the air below to undergo, alternatively, vertical shrinking and vertical stretching. With these assumptions in mind, figure 2G suggests that the bounded wave has a full amplitude close to 750 m and a period of about 2 hr. A simple expression for mass conservation can be used:

$$h_0|V_0|=h_1|V_1|. \tag{1}$$

The approximate height of the base of the inversion (AA) above sea level is 850 m (930–940 mb, fig. 3) and the mean integrated wind speed upstream from the island

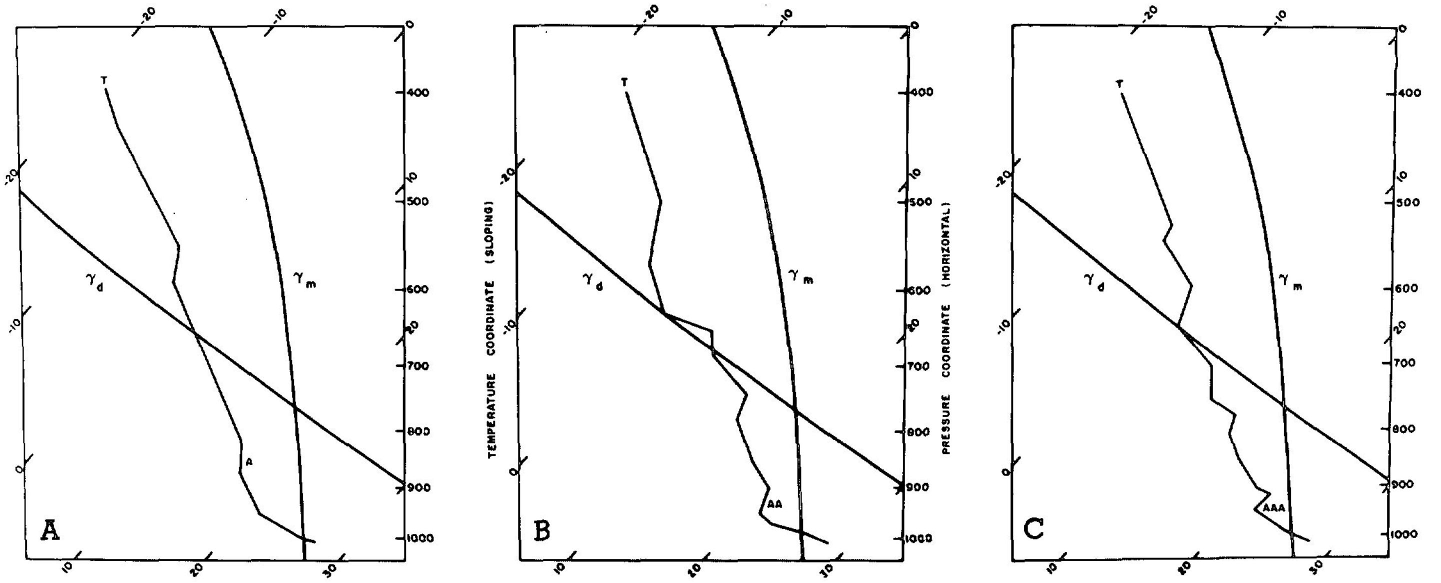

FIGURE 3.—Seawell Airport temperature soundings for (A) 0000 and (B) 1200 GMT on July 16, 1969, and (C) 0000 GMT on July 17, 1969. Letters A, AA, and AAA indicate inversion layers.

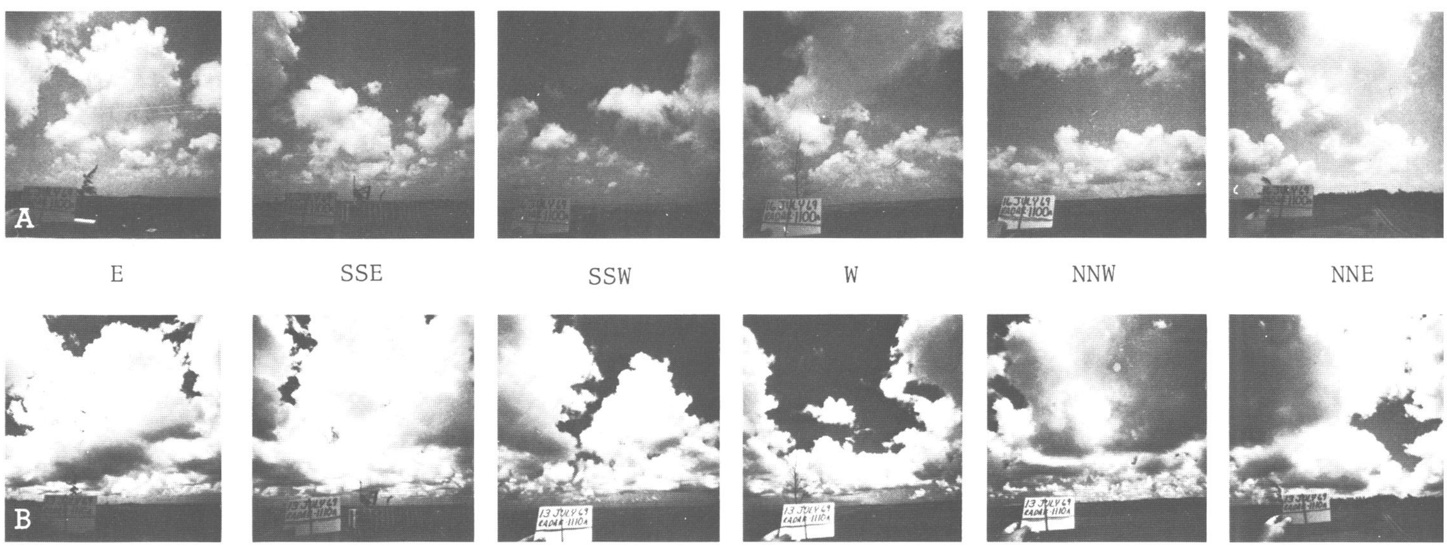

FIGURE 4.—(A) panorama of the cloud field at 1100 LST from station 2 on July 16, 1969; (B) panorama of the cloud field at 1110 LST from station 2 on a more typical day, July 13, 1969.

is estimated to be about 11 m/s (fig. 2C, 2H). When one uses eq (1), the corresponding wind speed V_1 through the column of height h_1 (450 m above the surface) over site 2 at the time of the passage of the wave trough would be 21 m/s. This is in reasonable agreement with the mean value of about 30 m/s observed at 1130 LST (1530 GMT). See figures 2B and 2G.

The wave-inversion phenomenon is schematically represented in figure 5. It is postulated that the undulation occurs along and, due to the lack of a solid limiting boundary, above the inversion. The turning of the wind is most pronounced through the inversion layer itself with the southeasterlies lying above the inversion. The amplitude and wavelength of the wave as schematically represented in figure 5 are best shown by this band of southeasterly winds. We suggest that the inversion undergoes a corresponding oscillation. The phase speed of this wave appears to be slower than the speed of the basic current so that the wave progresses slowly southwestward across the island. The Venturi effect, postulated above, is maximized when the trough of the wave coincides with the region of maximum island elevation. The maximum wind speeds then advance across the island as shown in figures 1B, 1C, and 1D in conjunction with the slower phase speed of the wave.

A computation of the Brunt-Väisälä frequency based on the available thermodynamic information of the environment is also made. The Brunt-Väisälä frequency that represents the upper boundary of the frequency

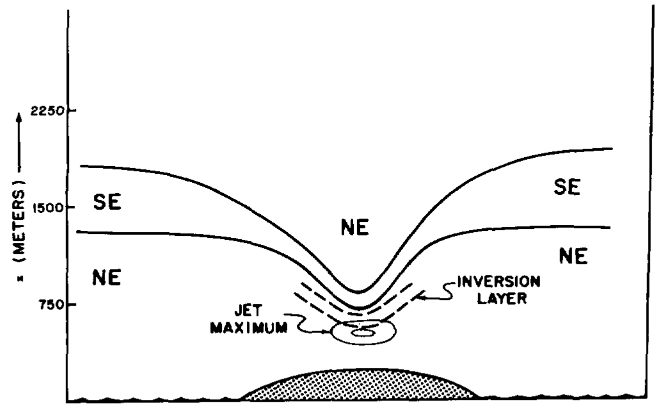

FIGURE 5.—Schematic representation of wave-inversion phenomenon. The southeasterly winds lie just above the top of the inversion layer and are depicted as delineating the top of the inversion with time.

range of possible modes of internal gravity waves (Holmboe et al. 1945, Angell et al. 1969) is given by

$$N=2\pi\left[\frac{T_0}{g(\gamma_p-\gamma_e)}\right]^{1/2} \tag{2}$$

where γ_p is the process lapse rate and γ_e is the environmental lapse rate (where the lapse rate is defined as the change of temperature with height). When one assumes a moist adiabatic process, N yields a period of 10 min. If on the other hand a dry adiabatic process is used, N gives a period of 5 min. It appears that the true Brunt-Väisälä period in the observed inversion layer AA lies between 5 and 10 min. This is much smaller than the period of the observed undulations in the time cross-section at site 2. This result is in agreement with the suggestion that these undulations reflect one of the internal gravity modes that are possible under the given stratification.

4. CONCLUDING REMARKS

Observations have been presented that show the existence of a low-level jet in a tropical location. The available information indicates that there are certain conditions necessary for its formation: (1) pronounced subsidence, (2) an obstacle with a height below the subsidence inversion level, and (3) an extended lower layer of unstable stratification beneath the inversion.

Numerous islands in the Tropics must experience these conditions. The question, therefore, arises as to why this feature has not been found more frequently?

Several reasons might be advanced. The meteorological stations are usually located in coastal areas because they tend to be associated with civil aviation facilities. This fact reduces the likelihood of observing the jet phenomena. Also, a radiosonde balloon with an ascent rate of 300–400 m/s and with a reading every minute makes a rather unsuitable instrument for detailed measurements in the atmosphere's lowest kilometer. Similarly, if a routine single theodolite pilot-balloon ascent penetrated a low-level jet, then it is likely that the observations would be discarded in the absence of additional substantiating evidence of high wind speeds.

This jet phenomenon may represent an added hazard to aircraft approaching or leaving airport runways. If such a feature occurs within the space of low-level aircraft operations, it would be very meaningful for the pilot to be alerted of its existence so that necessary compensations for the high wind shears could be applied.

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